# FREE-FIELD GROUND SHOCK PRESSURES FROM BURIED DETONATIONS IN SATURATED AND UNSATURATED SOILS

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## ABSTRACT

Free-field ground shock pressures at various distances from the buried detonation of high-explosive charges, mortar and artillery rounds, and large bombs have been measured by Southwest Research Institute and independently by Waterways Experiment Station personnel. This paper presents an empirical solution capable of predicting these pressures in unsaturated soils. In saturated soils, a very different energy dissipation process occurs which is predicted by modifying a hydrodynamic solution, and comparing it to tests on bombs in saturated soils.

## INTRODUCTION

We have been developing a general solution for predicting ground shock pressures and impulses imparted to shelters from the detonation of buried ordnance. Unfortunately, all the results cannot be shown in this short paper; however, one aspect, free-field ground shock pressures, will be presented in detail. Those wishing additional details can refer to reference [1].

Our solution was developed using modeling techniques and test results from a large compilation of ground shock pressure data. Under most conditions, a log-linear curve fit can be used to predict pressures over four orders of magnitude in value. The exception to the general solution arises when soils are saturated. Then, a modified hydrodynamic solution works. In this paper, we will present the general solution, compare results to measured pressures, show that problems can arise and derive the modified hydrodynamic solution.

## GENERAL SOLUTION

An empirical equation for predicting free-field ground shock pressure from the detonation of buried explosive is given by:

$$\frac{\left(\frac{P}{\rho c^2}\right)}{\left(4.35+\frac{Y}{d}\right)\left[0.25+0.75\tanh\left(0.48\frac{\rho^{1/3}c^{2/3}d}{W^{1/3}}\right)\right]} = 0.0175\left(\frac{W^{1/3}}{\rho^{1/3}c^{2/3}R_{eff}}\right)^{3.42} \qquad (1)$$

where $P$ = maximum pressure $(F/L^2)$

$\rho$ = mass density of soil $(FT^2/L^4)$

$c$ = speed of sound in soil $(L/T)$

$d$ = depth of ordnance buried to its C.G. $(L)$

$Y$ = depth of point below C.G. of ordnance $(L)$

$W$ = energy release of explosive $(FL)$

$R_{eff}$ = effective slant range which accounts for ordnance geometry and orientation $(L)$.

All ratios in Equation (1) are nondimensional which means that predictions can be made using any self-consistent set of metric or English units. The quantity $R_{eff}$ accounts for bomb length $\ell$ and orientation $\theta$. This quantity $R_{eff}$ is a first approximation to where an equivalent point source of the same energy release should be located so that the same scaled energy $W/\rho c^2R^3$ occurs for the distributed energy in a line source of finite length as in the equivalent point source. $R_{eff}$ is given by:

$$\frac{R_{eff}}{\ell} = \left[\frac{M - N^2 - \frac{1}{4}}{\frac{N+0.5}{(M+N)^{1/2}} - \frac{N-0.5}{(M-N)^{1/2}}}\right]^{1/3} \qquad (2)$$

where $M = (Z/\ell)^2+(X/\ell)^2+(Y/\ell)^2+1/4$

$N = (Y/\ell)\cos\theta+(Z/\ell)\sin\theta$

and $Z$ = horizontal distance of location in vertical plane through the bomb $(L)$

$X$ = transverse distance of location $(L)$

$\ell$ = length of explosive source $(L)$

$\theta$ = bomb's orientation ($\theta$=0 degrees is a vertical bomb).

## COMPARISON WITH DATA

Equation (1) has a format permitting scaled pressure on the left-hand side of the equation to be plotted versus a scaled effective standoff distance on the right-hand side. Many different symbols are seen in Figure 1 because there were many variations in size of explosive energy release (1.8, 0.327, and 0.216 lb sources), orientation of the charge (0, 90, and 45 degrees), depth of burial

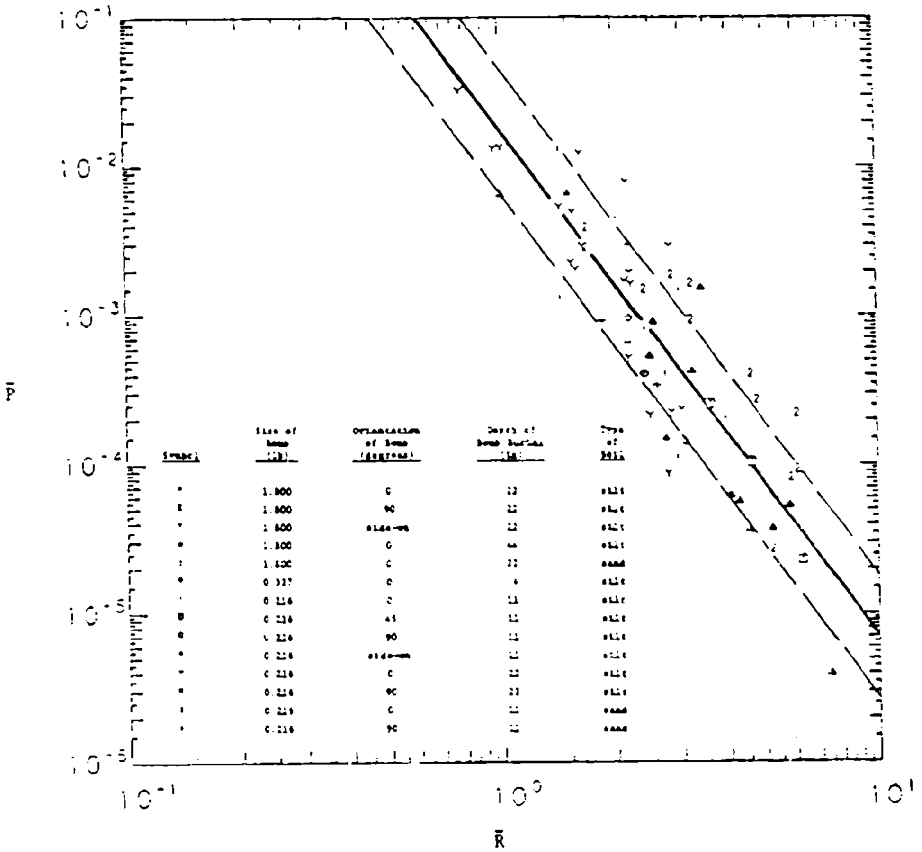

Figure 1. Scaled Pressure Versus Distance in SwRI Tests

of the charge, (4, 11, and 22 inches) depth of burial of transducer, and type of soil (silt and sand). All tests were performed outdoors with a natural variation in soil conditions recorded by measuring soil density $\rho$ and velocity $c$ during each test.

The solid line through the pressure data is Equation (1). The dashed line on each side of the prediction line is a statistical one sigma standard deviation for a normal distribution in log of pressure about the prediction line. Although this scatter may appear to be large, it is of the same magnitude for results from other experiments.

Personnel at Waterways Experiment Station [2] have been conducting tests in which free-field ground shock pressures were monitored at various sites around buried C-4 charges, mortar shells, howitzer rounds, and bombs. In Figure 2 our solution and its scatter is shown so it can be compared to ground shock pressures for 155-mm howitzer shells containing 15.6 lb of TNT, 105-mm howitzer shells containing 4.8 lb of Comp-B, and 4.2-inch mortar shells with 7.8 lb of TNT fired at White Sands Missile Range.

A final comparison conducted at White Sands by WES personnel involved 16, 5, and 8-lb explosive C-4 charges. These scaled pressures are compared to Equation (1) in Figure 3. Because the results seen in Figures 2 and 3 are similar to those seen in Figure 1, the same comments about accuracy and scatter apply.

## HYDRODYNAMIC SOLUTION

At another test site, Fort Knox, Kentucky, WES personnel conducted ground shock pressure measurements using live MK-82 (500-lb) and MK-84 (2000-lb) bombs. These bombs contain, respectively, 191 lb and 945 lb of tritonal. Measured pressures were all higher than expected as can be seen by looking at the results in Figure 4. A reason does exist for these pressures being higher than expected, but to understand, we must discuss Fort Knox field conditions.

The soil at Fort Knox is a 10 foot upper layer of soft brown clay overlying a soft clay mixed with gravel. The density of both layers is the same average wet density of 125 lb/ft$^3$ and water content of 22.5 percent. The major difference between the layers is that the upper layer has a P-wave velocity of 1200 ft/sec; whereas, the lower layer has a

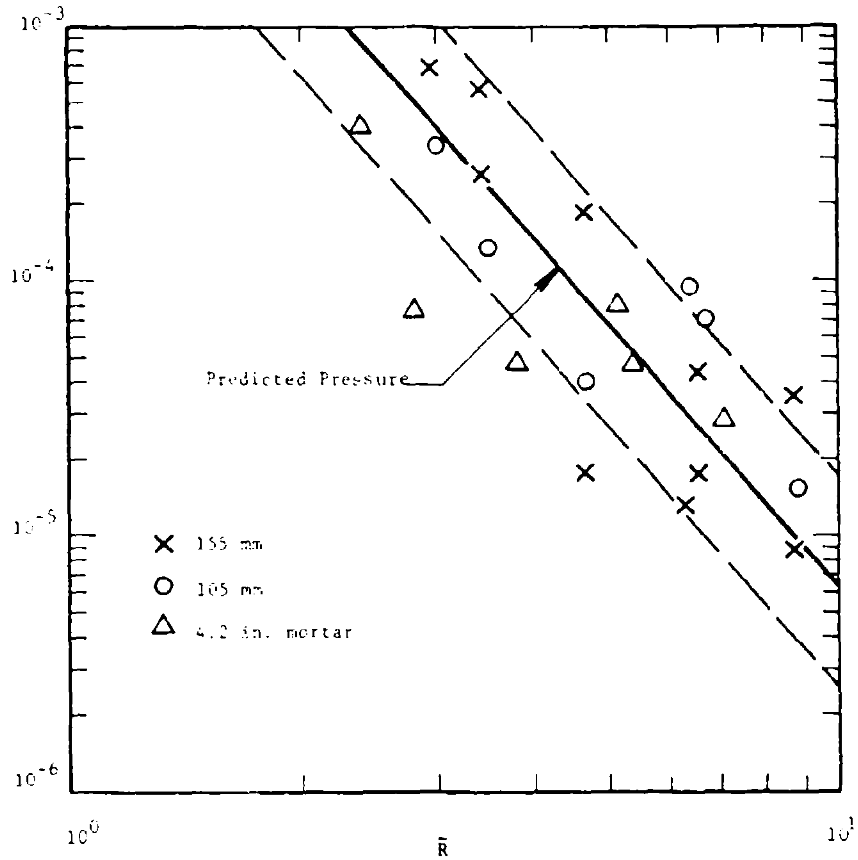


Figure 2. Comparison of Free-Field Pressure Solution to Test Results with 155-mm Artillery Shells

velocity of 4800 ft/sec. Both soils are essentially saturated with the ground water table at the 10-foot depth separating these layers. The upper layer is saturated by capillary action. The change in seismic velocity from 1200 to 4800 ft/sec demonstrates the existence of the ground water table at the 10-foot depth, because 4800 ft/sec is the speed of sound in water.

All other test sites were much drier than Fort Knox. Moisture contents did reach 12 percent, but these are low relative to 22.5 percent. When the pores of a soil are filled with water rather than air, an almost incompressible pore fluid exists. Energy dissipation associated with collapse of the pores and shearing of soil grains over each other is not as great, and pressures are, therefore, higher at various standoff distances.

Instead of using a soil solution, the propagation of shock through saturated soils can be approximated by modifying a solution for shocks in water. In his book on underwater explosions, Cole [3] presents test data which can be curve-fitted using a log-linear approximation to give an equation for shock pressures in water.

$$P(\text{psi}) = 24{,}650 \left[\frac{W^{1/3}(\text{lb TNT})^{1/3}}{R\ (\text{ft})}\right]^{1.16} \qquad (3)$$

By inserting the invarient $\rho$ and c into Cole's dimensional equation, converting Equation (3) to a self-consistent set of dimensionless units, assuming that $\frac{\rho^{1/3}c^{2/3}d}{W^{1/3}}$ is large, and that the pressure gauge and bomb are at the same depth, Equation (3) can be rewritten as:

$$\left[\frac{P}{4.35\rho c^2}\right] = 0.04224 \left[\frac{\rho^{1/3}c^{2/3}R}{W^{1/3}}\right]^{-1.16} \qquad (4)$$

Equation (4) is the hydrodynamic equation which is shown in Figure 4 and compared to the unsaturated soil solution and test data on MK-82 and MK-84 bombs. As can be seen, the hydrodynamic solution works much better and predicts much higher scaled pressures. The Fort Knox test site with its high ground water table behaves like a liquid. That is to say, provided one assumes that the bombs are in a special "heavy water" with a weight density of 125 $lb/ft^3$ and water that propagates shocks at the measured P-wave velocity, either 1200 ft/sec for shallow burials above 10 feet or 4800 ft/sec

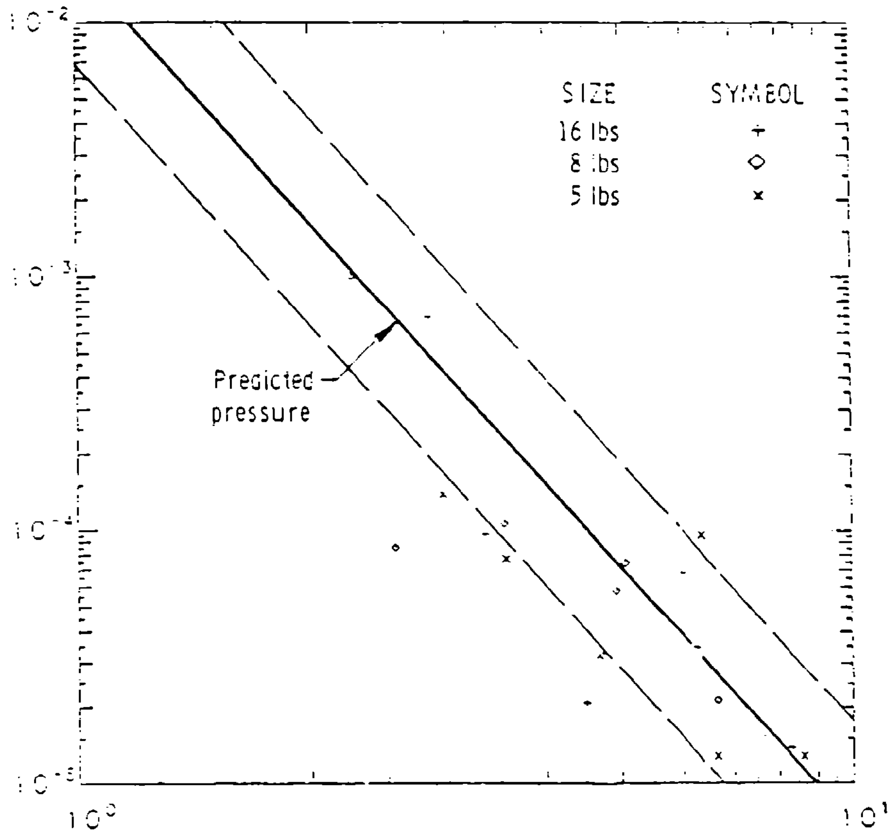


Figure 3. Pressure Versus Distance for WES C-4 Charges

below the ground water table, energy is not dissipated as rapidly in saturated soils, and test results appear to be predicted by this modified hydrodynamic solution.

Obviously some transition regime must exist between the soil and water solutions. Although the data to demonstrate when and how a transition occurs are unavailable for degrees of saturation equal to or less than 50 or 60 percent, the soil solution is recommended. Further study is required to understand and separate these two solutions.

## CONCLUSIONS

This paper only presents the results from one small segment of a large report containing information on free-field, oblique, and normally reflected ground shock pressures. In this report, impulse as well as pressures are studied and details are presented on how predictive equations and the $R_{eff}$ concept are derived and test results measured.

In this particular discussion, we showed that free-field ground shock pressures dissipate in very different manners dependent upon whether soils are saturated or unsaturated. Empirical equations are presented which allow free-field pressures to be predicted at various standoff distances in saturated and unsaturated soils. Test data from a variety of buried ordnance detonations are presented in dimensionless format to demonstrate the validity of these solutions.

## References

[1] Peter S. Westine and Gerard J. Friesenhahn, Ground Shock Loads From Buried Bomb and Ordnance Detonations, U.S. Air Force Armament Laboratory, Eglin Air Force Base, Florida, Report No. AFATL-TR-82-19, 1982.

[2] As yet unreported data, obtained through personnal correspondence with Waterways Experiment Station.

[3] Robert H. Cole, Underwater Explosions, Dover Publications, Inc., New York, 1948, p 240.

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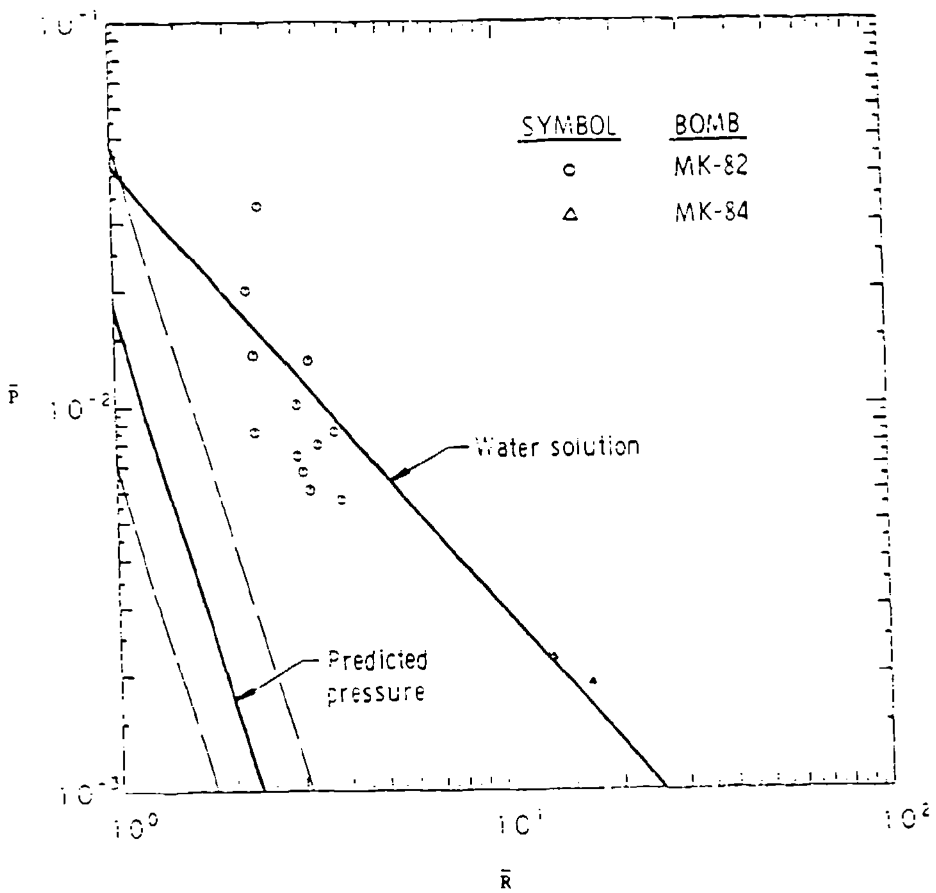


Figure 4. Pressure Versus Distance in Saturated Fort Knox Soils

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